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TECHNICAL MEMORANDUM

X-642

FREE-FLIGHT MEASUREMENTS OF DRAG AND STABILITY OF A BLUNT-NOSED CYLINDER WITH A FLARED AFTERBODY IN AIR AND CARBON DIOXIDE

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FREE-FLIGHT MEASUREMENTS OF DRAG AND STABILITY OF A BLUNT-NOSED CYLINDER WITH A FLARED AFTERBODY IN AIR AND CARBON DIOXIDE*

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SUMMARY

The drag coefficient and static stability characteristics of a blunt-nosed cylinder with flared afterbody were obtained from free-flight tests in both air and mixtures of carbon dioxide gas and air. Tests were made at Mach numbers from 3 to 7 and Reynolds numbers from 2 to 4 million based on model length.

No apparent difference was found in comparing the drag results obtained in the two gases. The stability was nearly the same in the two gases at a Mach number of 3 but the stability decreased with increasing Mach number more rapidly in carbon dioxide than in air. The variation of stability with angle of attack was essentially the same in the two gases. Theoretical predictions of static stability were made using the method of NASA TM X-377, 1960.

INTRODUCTION

Plans are being made for the exploration of the near planets, Venus and Mars, with instrumented probes and ultimately with manned vehicles. To accomplish flight within the atmospheres of these near planets, some knowledge of the constituents of their atmospheres and the gasdynamics of the constituents must be determined. The only gas that has been detected in any sizable amount on either Venus or Mars is carbon dioxide (ref. 1). However, the quantity detected in the atmosphere of Mars accounts for only a few percent of the total atmosphere and the remainder has been assumed to be nitrogen, whereas the quantity of carbon dioxide in the atmosphere of Venus appears to account for a large amount (as much as

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90 percent) of that atmosphere. From this it appears that the Venus atmosphere is markedly different from that of the earth and the atmosphere of Mars may not be appreciably different from that of earth for aerodynamic considerations.

Comparison of the thermodynamic properties of carbon dioxide and air at temperatures associated with post entry flight conditions showed that while both satisfy the thermal equation of state, they have noticeably different caloric equations of state. Air is calorically perfect (constant specific heats) at low temperatures and only becomes calorically imperfect at high temperatures, whereas carbon dioxide is calorically imperfect at all temperatures for which it exists as a gas. The purpose of this study was to determine whether any differences in the aerodynamic characteristics of vehicles would exist in carbon dioxide and air as a result of the different variation of specific heats with temperature.

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An experimental investigation was conducted in the Ames Supersonic Free-Flight Wind Tunnel with air and carbon dioxide as test mediums. Although the exact nature of the atmosphere of Venus is still in question both as to chemical composition and temperature, a mixture of nominally 90-percent carbon dioxide and 10-percent air at ambient temperature was used in these tests to represent that atmosphere. The tests were made over a Mach number range from 3 to 7 and over a Reynolds number range from 2 to 4 million based on model length. A blunt-nosed cylinder with a flared afterbody was chosen as the model for these tests.

SYMBOLS

A	area based on cylindrical cross section, ft^2
c_p	specific heat at constant pressure, $\frac{\text{Btu}}{\text{slug } ^\circ\text{R}}$
$(c_p)_{per}$	c_p for a thermally and calorically perfect gas, $\frac{\text{Btu}}{\text{slug } ^\circ\text{R}}$
c_v	specific heat at constant volume, $\frac{\text{Btu}}{\text{slug } ^\circ\text{R}}$
$(c_v)_{per}$	c_v for a thermally and calorically perfect gas, $\frac{\text{Btu}}{\text{slug } ^\circ\text{R}}$
$(c_v)_{vib}$	specific heat due to vibration of molecule, $\frac{\text{Btu}}{\text{slug } ^\circ\text{R}}$
C_D	drag coefficient, $\frac{\text{drag}}{qA}$

C_m — pitching-moment coefficient, $\frac{\text{pitching moment}}{qAl}$

$C_{m_{\alpha_L}}$ — pitching-moment-curve slope (linearized), per radian

C_{N_α} — normal-force-curve slope, per radian

d — diameter of model, ft

I_y — transverse moment of inertia, slug-ft^2

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K — constant obtained from model measurements, $\frac{-8\pi^2 I_y}{Al}$, slugs/ft

l — length of model, ft

m — mass of model, slugs

M — Mach number

R — gas constant, $\frac{\text{Btu}}{\text{slug }^\circ\text{R}}$

T — temperature, $^\circ$R

T_t — stagnation temperature, $^\circ$R

x_{cg} — length from model nose to center of gravity, ft

α — angle of pitch (in vertical plane), deg

β — angle of yaw (in horizontal plane), deg

α_R — $\sqrt{\alpha^2 + \beta^2}$, deg

γ — ratio of specific heats, $\frac{c_p}{c_v}$

λ — wave length of pitching cycle, ft/cycle

ρ — density, slugs/ft^3

APPARATUS AND TEST PROCEDURE

The tests were performed in the Ames Supersonic Free-Flight Wind Tunnel by launching the models from a 0.5-inch-diameter smooth-bore gun into either a Mach number 2 countercurrent airstream or a quiescent mixture of carbon dioxide and air at ambient temperature and pressure. For the tests in air in the wind tunnel, the reservoir pressure was adjusted, at ambient temperature, to match the Reynolds number obtained for tests in carbon dioxide. The Reynolds numbers then varied from slightly less than 2 million at a Mach number of 3, to 4 million at a Mach number of 7. Gas samples were taken before, during, and at the end of each series of firings for the tests in carbon dioxide. These were analyzed for carbon dioxide content on a spectrograph and the results are given in table I as percent by volume.

The models used in these tests were blunt-nosed cylinders with flared afterbodies. A photograph of a model with its sabot is shown in figure 1, and a drawing of the model is presented in figure 2. Model center-of-gravity locations are given for models fired into the carbon dioxide mixture in table I and for models fired into air in table II.

Data were taken at nine stations along a 24-foot test section and consisted of shadowgraphs of the model in pitch and yaw and a time-distance history obtained by chronographs. The wind tunnel and its instrumentation are described in reference 2.

Aerodynamic drag coefficients and the static stability derivative, $C_{m_{\alpha_L}}$, were obtained from the time-distance-attitude history of the model. The model performed approximately 1 cycle of free oscillation about a transverse axis through its center of gravity during the recorded flight. In these tests, various amplitudes of oscillation were obtained with a maximum value of about 20°. Drag coefficients were computed from the deceleration of the models and the static stability derivatives were computed from the equation (ref. 2)

$$C_{m_{\alpha_L}} = \frac{-8\pi^2 I_y}{\lambda^2 \rho A l} = \frac{K}{\lambda^2 \rho}$$

where K was determined from measurements of each model. The subscript L denotes the assumption of a linear variation of pitching moment with angle of attack.

Data were obtained at two Mach numbers in both air and carbon dioxide for models with two different center-of-gravity positions, although the majority of the tests were with the model shown in figure 2. Tests were also made at $M = 7$ with various mixtures of air and carbon dioxide to determine the effect of carbon dioxide concentration on $C_{m_{\alpha_L}}$.

THEORY

Intuitively, differences may be expected in the aerodynamic forces measured in air and in carbon dioxide since certain flow phenomena depend on the caloric properties of the gas. Also, the vehicle shape will affect these flow phenomena. The differences in the caloric equations of state for air and carbon dioxide are due to the different amounts of vibrational energy possessed by the molecules in equilibrium at a given temperature. The variation of the dimensionless specific heat of vibration $(c_v)_{vib}/R$ is shown in figure 3 as a function of temperature. The corresponding variation in

$$\gamma = \frac{c_p}{c_v} = \frac{(c_p)_{per} + (c_v)_{vib}}{(c_v)_{per} + (c_v)_{vib}}$$

is also shown. For the range of temperatures considered herein, the vibrational energy for carbon dioxide is always greater than that for air. Since the flow through a normal shock wave is dependent upon this energy, it would seem reasonable that this blunt-nosed model could have different characteristics in carbon dioxide and air.

Theoretical pressure distributions obtained by the method described in reference 3 were used to estimate the aerodynamic stability of the model. It was shown in the reference that this procedure satisfactorily predicts the static stability of a blunt-nosed body in air. It then remains to consider the effects of a calorically imperfect gas. Although the theoretical method (ref. 3) is not limited to perfect gases, the only digital computer program available for this method was the perfect gas case. Because of this, the calculations were made using a fictitious perfect gas with a value of γ corresponding to the stagnation temperature for the particular test conditions. This procedure uses the extreme value of γ even though the temperature of the gas, and consequently γ, varies considerably in the flow field surrounding the model. These calculations are only intended to give a first approximation of the effect of a varying ratio of specific heats.

RESULTS AND DISCUSSION

The results of this investigation permit a comparison of some of the aerodynamic characteristics of a blunt-nosed cylinder with flared afterbody in both a gas which had a high degree of caloric imperfection (90-percent concentration of carbon dioxide in air) and in air which for this study had only a comparatively small degree of caloric imperfection. All of the data taken in the carbon dioxide mixtures are presented in table I and all of the data taken in air are presented in table II. Most of the air data are from reference 4. A limited amount of data obtained with the model center of gravity in a more forward position verified the results obtained with the standard model. Since only one shape was tested, these results are not generally applicable to all shapes. However, some of the real gas effects on the aerodynamic stability of this model may be indicative of those for flare-stabilized, or possibly fin-stabilized, blunt-nosed vehicles.

A comparison of the measured aerodynamic drag coefficient in air and in a mixture of 90-percent carbon dioxide and 10-percent air is presented in figure 4. No significant differences are apparent for this model
within the range of experimental variables. Only total drag was measured A
and no efforts were made to separate these values into friction drag, 5
base drag, and so forth. 7
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The stability parameter $C_{m_{\alpha_L}}$ is shown in figure 5 plotted as a function of amplitude of oscillation for Mach numbers of 5 and 7. These linearized stability parameters have been used to compute the static pitching-moment coefficients (by the method of ref. 5) which are presented in figure 6. It is clear from these figures that the static stability is appreciably lower in the carbon dioxide and air mixture than in air for amplitudes less than 10°. This difference becomes less pronounced at higher amplitudes where the restoring moment is quite large. It is also noted that the variation of stability with angle of attack is essentially the same in the two gases.

The experimental data for small amplitudes of oscillation (less than 6°) have been used in figure 7 to show the variation of the static stability parameter $C_{m_{\alpha_L}}$ with Mach number for flight in air and in the carbon dioxide and air mixture. Also included in this figure are the predicted variations obtained by the method previously discussed. A loss of static stability with increasing Mach number is noted both in air and carbon dioxide with the rate of deterioration more rapid in carbon dioxide. The loss of stability with increase in speed in the hypersonic range for blunt-nosed slender bodies in air has been previously reported by Seiff and Whiting (ref. 3), wherein it was shown that the shock wave is forced away from the body by the blast-wave effect of the blunt nose. Figure 8 shows this effect in carbon dioxide is similar to that in air. A decrease in stability with increasing Mach number due to the loss of dynamic pressure in the vicinity of the flare is predicted by the theoretical method used. Although this method (using a fictitious perfect gas with a value of γ corresponding to the stagnation temperature for the particular free-stream Mach number) overpredicts the level of stability, the variation of stability with Mach number agrees with the experimental trend both for carbon dioxide and for air. The significant result of the comparison in figure 7 is that both theory and experiment show a greater decrement of stability with increasing Mach number in carbon dioxide than in air. It thus appears that the ratio of specific heats, γ, can have an important influence on the stability of blunt-nosed bodies.

Some tests were made at Mach number 7 in various mixtures of carbon dioxide and air. The results, shown in figure 9, indicate that a sizable reduction in stability, from that measured in air, occurred in a mixture containing only 33-percent carbon dioxide.

CONCLUDING REMARKS

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An experimental investigation to compare the aerodynamic characteristics of a blunt-nosed cylinder with flared afterbody in air and in a mixture of 90-percent carbon dioxide and 10-percent air revealed some differences which may be important in the design of spacecraft intended to fly in the atmosphere of Venus. Although the test gas had no effect on the model drag coefficient over the speed range of this study, a pronounced effect was noted on the static stability of the model. Comparable stability levels were measured in air and carbon dioxide at the lowest speed of these tests ($M = 3$). However, the stability decreased more rapidly in carbon dioxide than in air with increasing Mach number, at least for the speed range of this investigation. At a Mach number of 7, the model was significantly less stable in carbon dioxide than in air. The nonlinear variation of stability with angle of attack was essentially the same in both air and carbon dioxide.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Oct. 6, 1961

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2. Seiff, Alvin: A Free-Flight Wind Tunnel for Aerodynamic Testing at Hypersonic Speeds. NACA Rep. 1222, 1955.

3. Seiff, Alvin, and Whiting, Ellis: The Effect of the Bow Shock Wave on the Stability of Blunt-Nosed Slender Bodies. NASA TM X-377, 1960.

4. Kirk, Donn B.: Free-Flight Investigation of the Static Stability of Blunt-Nosed Flare-Stabilized Entry Bodies at Mach Numbers From 5 to 16. NASA TM X-584, 1961.

5. Kirk, Donn B.: A Method for Obtaining the Nonlinear Aerodynamic Stability Characteristics of Bodies of Revolution From Free-Flight Tests. NASA TN D-780, 1961.

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TABLE I.- TEST CONDITIONS AND RESULTS FOR CARBON DIOXIDE AND AIR MIXTURES

Test number	CO_2, percent	x_{cg}/l	$\alpha_{R_{max}}$, deg	M	$C_{m_{\alpha_L}}$	C_D
683	0.86	0.39	3.6	3.16	-0.461	1.467
676	.92	.40	5.8	4.89	-.179	1.409
677	.92	.32	3.9	4.91	-.254	1.462
678	.92	.39	3.0	5.02	-.185	1.455
684	.86	.39	5.4	5.02	-.210	1.392
680	.86	.39	2.5	5.05	-.167	1.415
704	.90	.39	19.2	5.12	-.787	1.641
741	.90	.39	15.0	5.18	-.356	1.463
736	.90	.39	11.5	5.20	-.290	1.514
705	.90	.39	18.6	5.28	-.768	1.628
779	.33	.39	15.0	6.65	-.416	1.522
762	.48	.39	16.0	6.65	-.636	1.698
760	.36	.39	15.5	6.66	-.502	1.516
778	.33	.39	4.2	6.67	-.110	1.476
781	.73	.32	8.8	6.70	-.317	1.482
782	.73	.32	12.8	6.72	-.538	1.559
702	.90	.40	.7	6.89	-.085	1.343
799	.87	.38	4.5	6.91	-.064	1.528
785	.83	.32	12.0	6.94	-.308	1.523
703	.90	.39	2.4	6.95	-.094	1.267
786	.83	.32	5.9	7.08	-.181	1.536
740	.90	.40	15.0	7.27	-.442	1.470
739	.90	.39	4.0	7.36	-.059	1.436

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TABLE II.- TEST CONDITIONS AND RESULTS FOR AIR

Test number	x_{cg}/l	$\alpha_{R_{max}}$, deg	M	$C_{m_{\alpha_L}}$	C_D
732	0.39	1.9	3.37	-0.487	1.627
[1]244	.39	13.6	4.75	-.417	---
[1]159	.38	13.2	5.05	-.377	1.455
[1]440	.39	12.8	5.06	-.368	---
[1]441	.39	2.6	5.12	-.293	---
[1]463	.38	12.1	5.12	-.356	---
[1]646	.32	4.5	5.14	-.335	1.424
[1]462	.37	12.0	5.16	-.344	---
[1]728	.39	17.0	5.16	-.589	---
[1]167	.38	12.3	5.19	-.330	1.464
[1]645	.32	1.2	5.22	-.353	1.413
[1]460	.38	2.4	5.25	-.290	---
[1]277	.38	11.7	5.26	-.297	1.463
[1]727	.39	17.2	5.26	-.616	---
[1]214	.38	10.8	5.29	-.295	1.480
[1]220	.39	13.4	5.30	-.384	1.462
[1]726	.39	18.6	5.32	-.713	---
742	.39	2.2	6.38	-.215	1.371
789	.32	5.5	7.05	-.280	1.351
788	.39	4.7	7.11	-.178	1.360
787	.39	13.8	7.21	-.486	1.396
860	.39	1.8	7.27	-.200	1.350
861	.39	7.2	7.50	-.180	1.326

[1]Data from reference 4.

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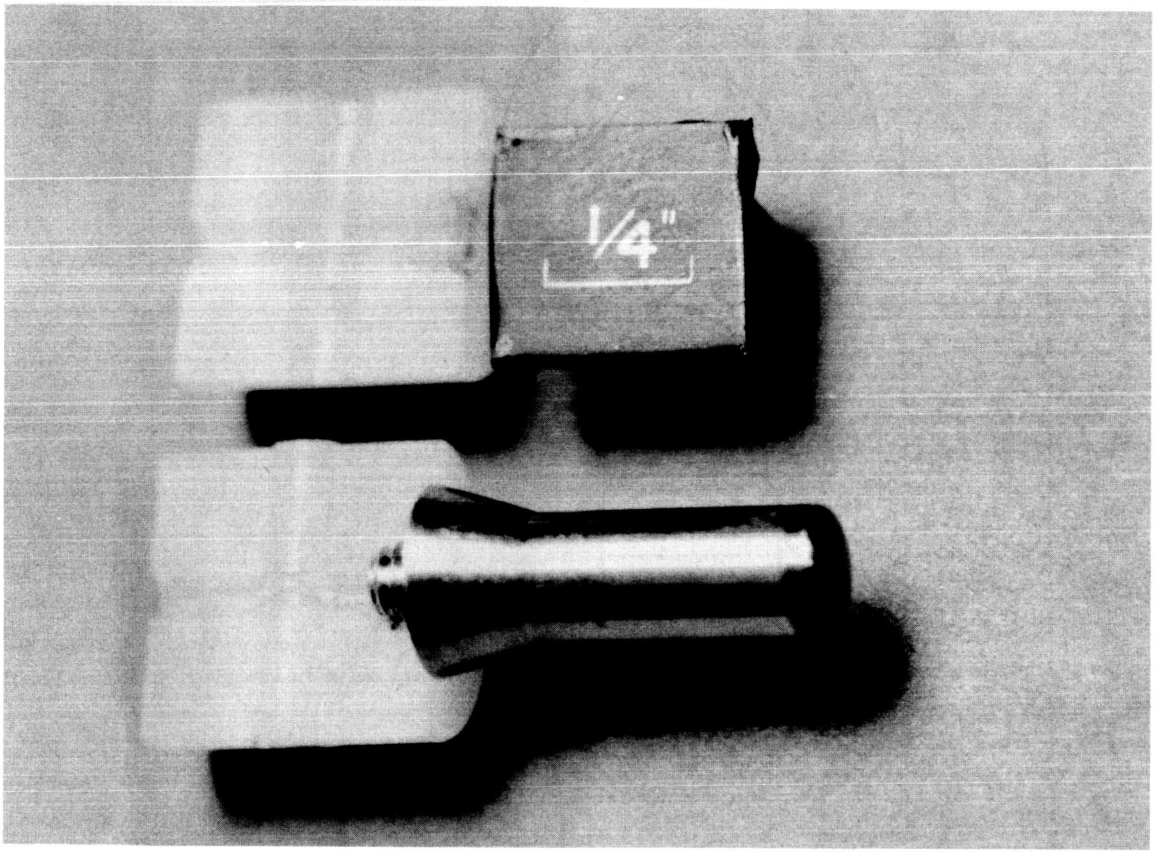

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Figure 1.- Photograph of model and sabot.

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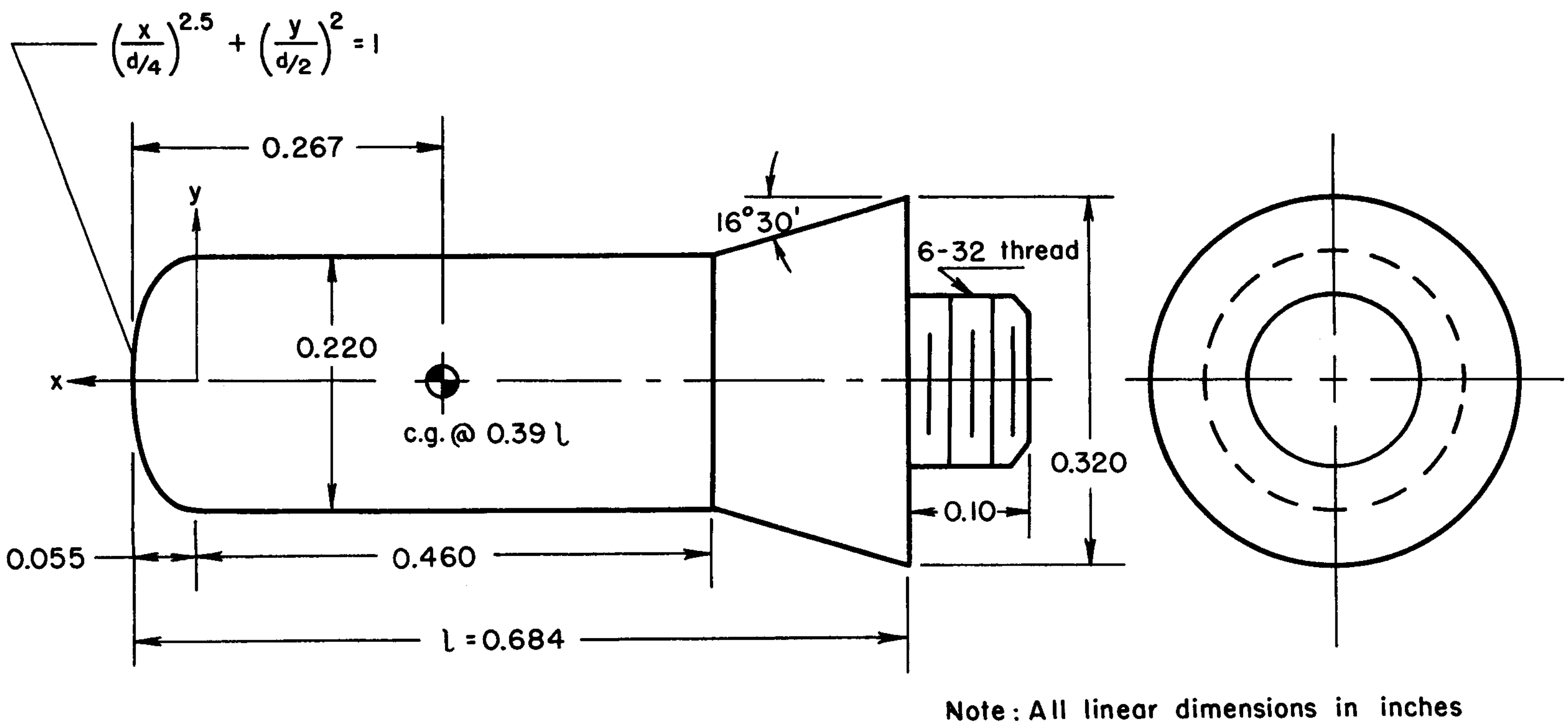

Figure 2.- Sketch of model.

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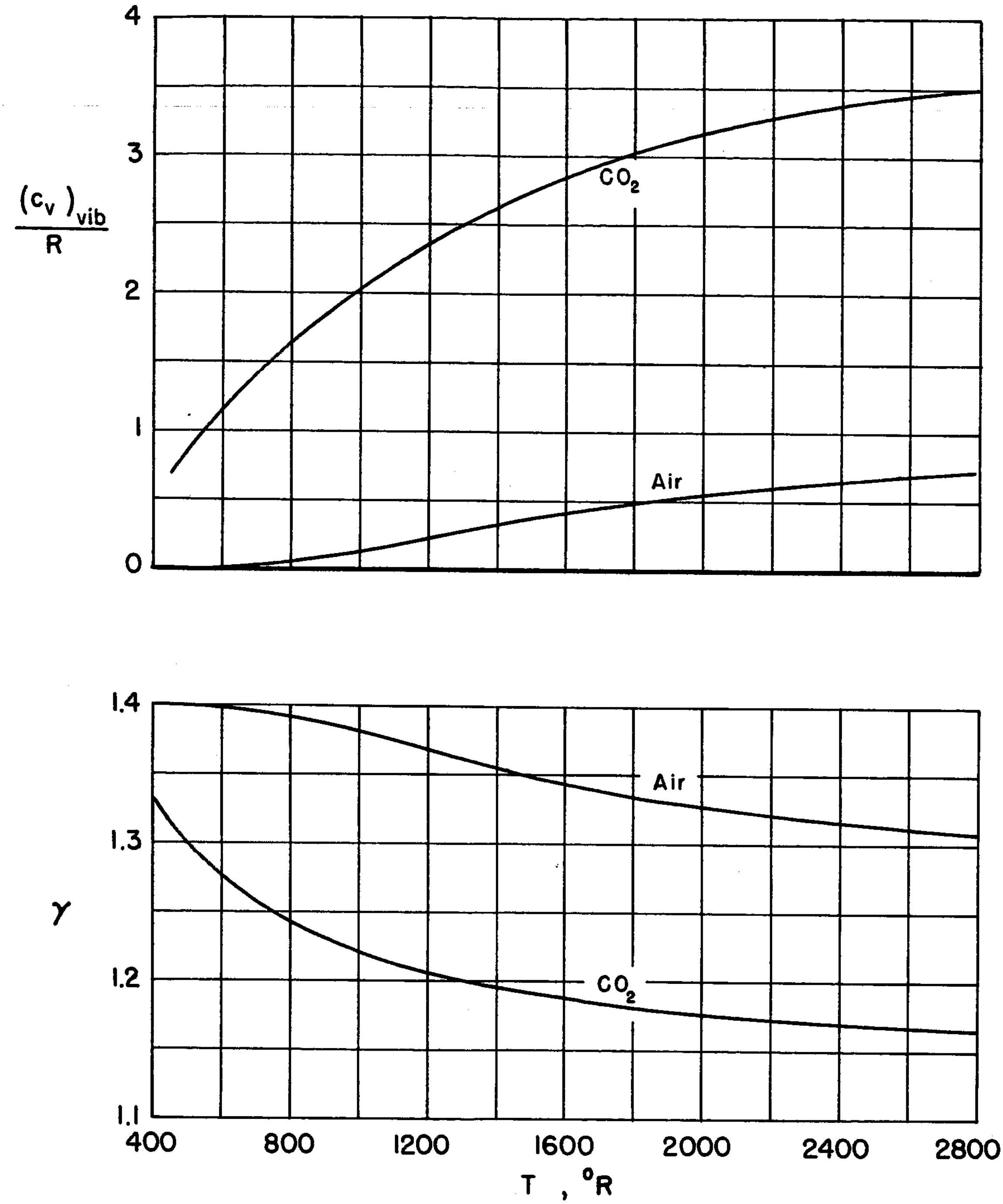

Figure 3.- Variation of specific energy of vibration and corresponding ratio of specific heats with temperature for air and carbon dioxide gas.

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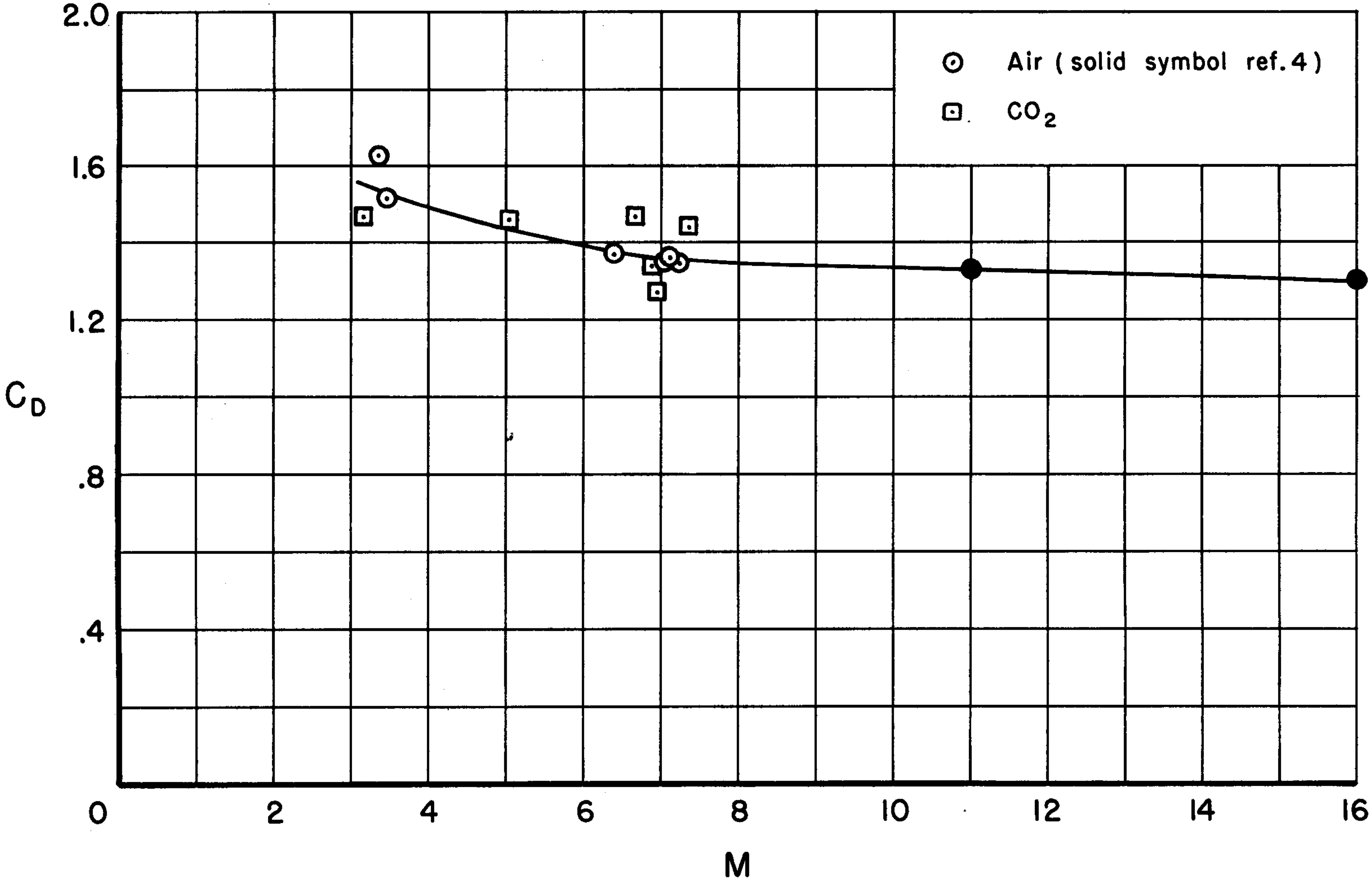

Figure 4.- Drag coefficients measured in air and a 90-percent carbon dioxide and air mixture; $\alpha_{R_{max}} = \pm 4^{\circ}$.

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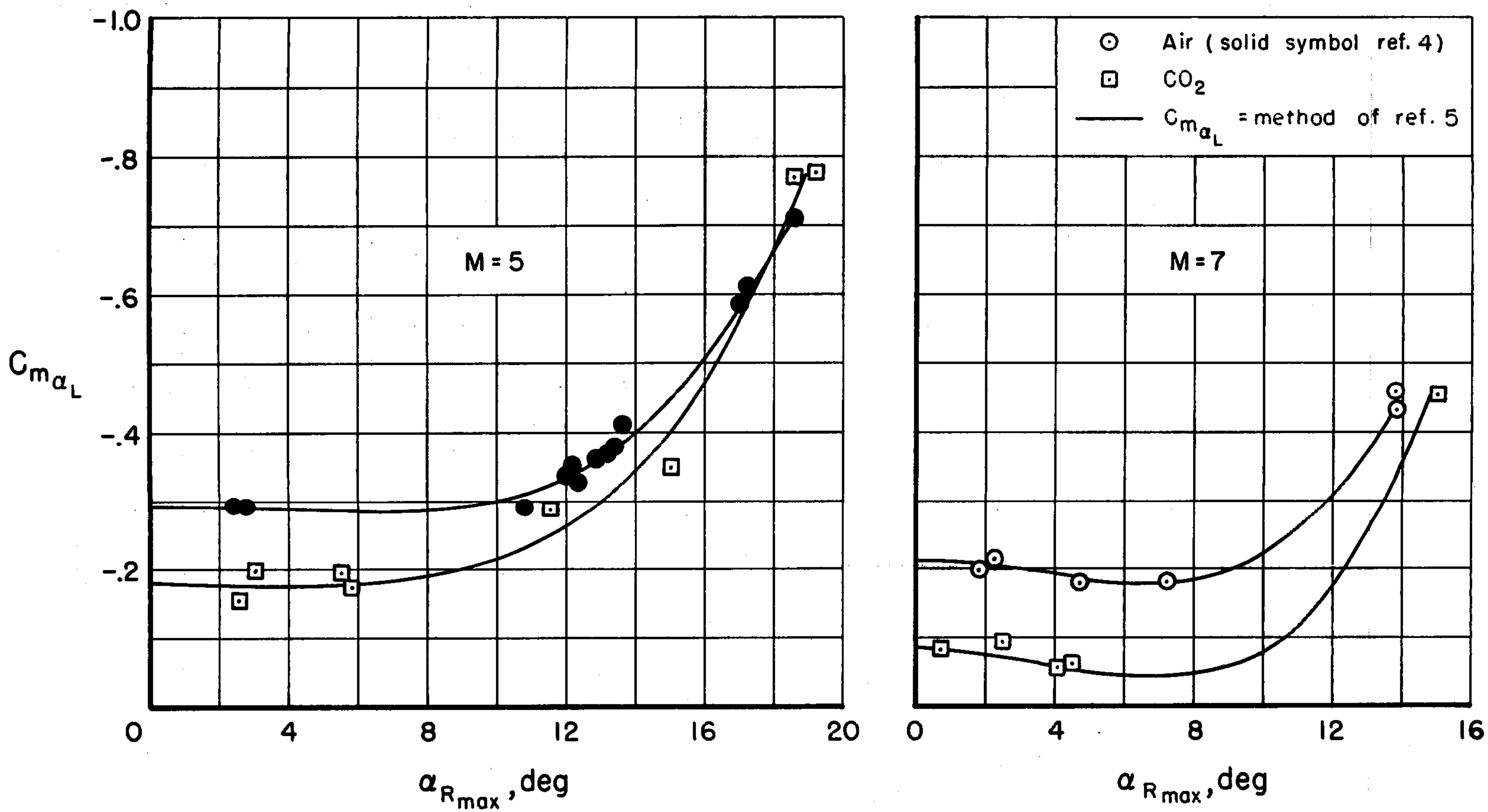

Figure 5.- Effect of amplitude of oscillation on the static stability derivative in air and a 90-percent carbon dioxide and air mixture.

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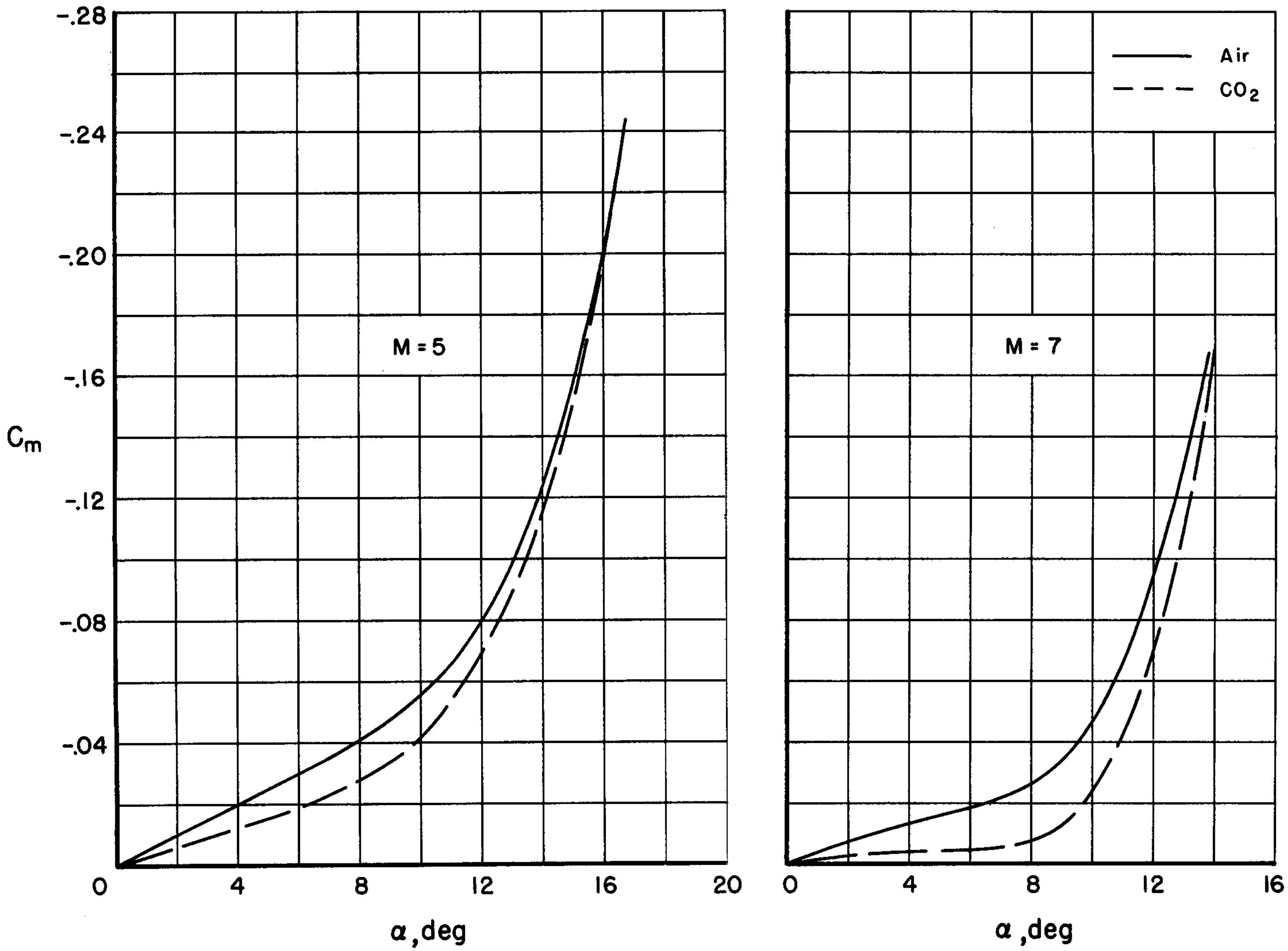

Figure 6.- Variation of pitching-moment coefficient with angle of attack in air and a 90-percent carbon dioxide and air mixture.

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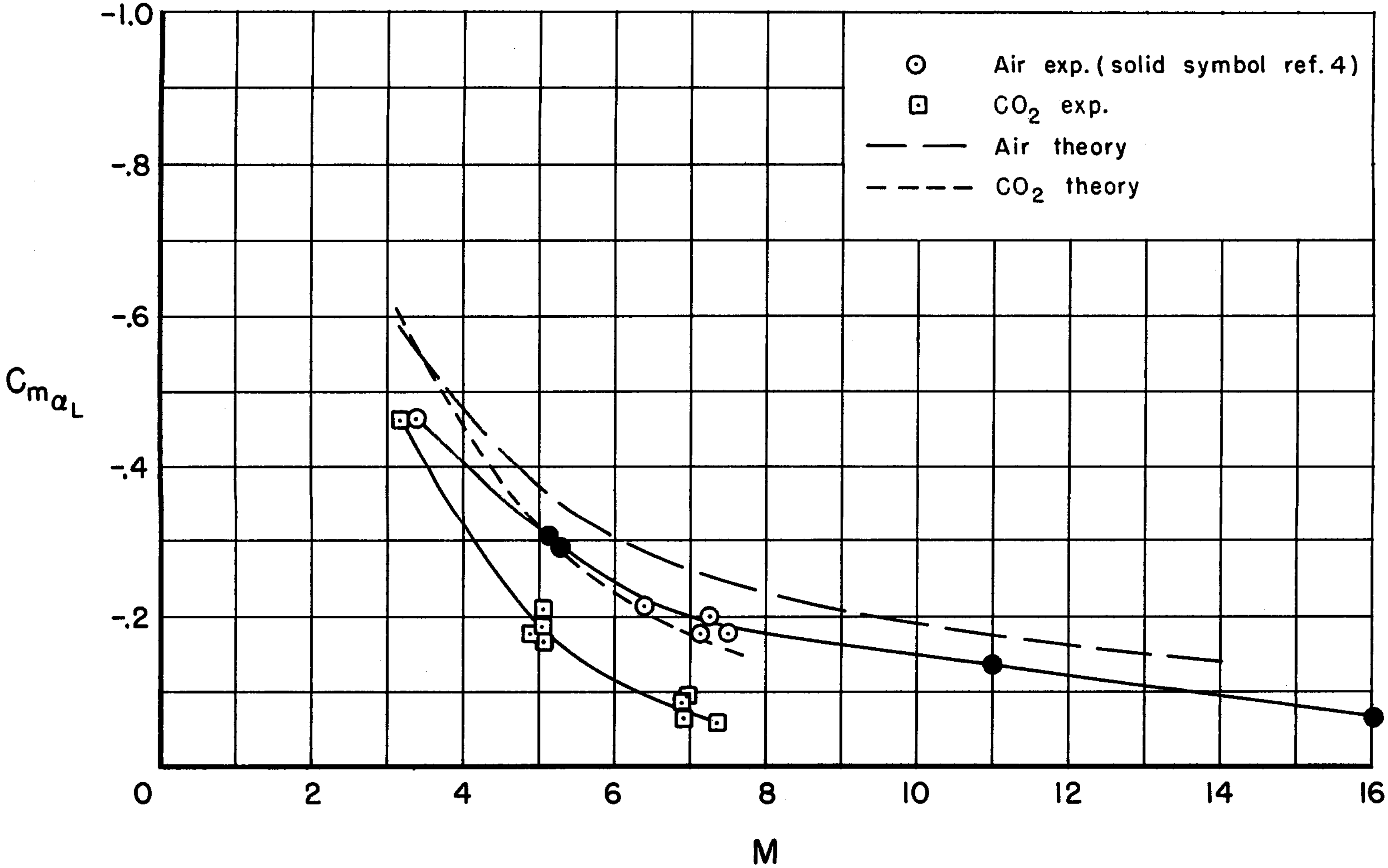
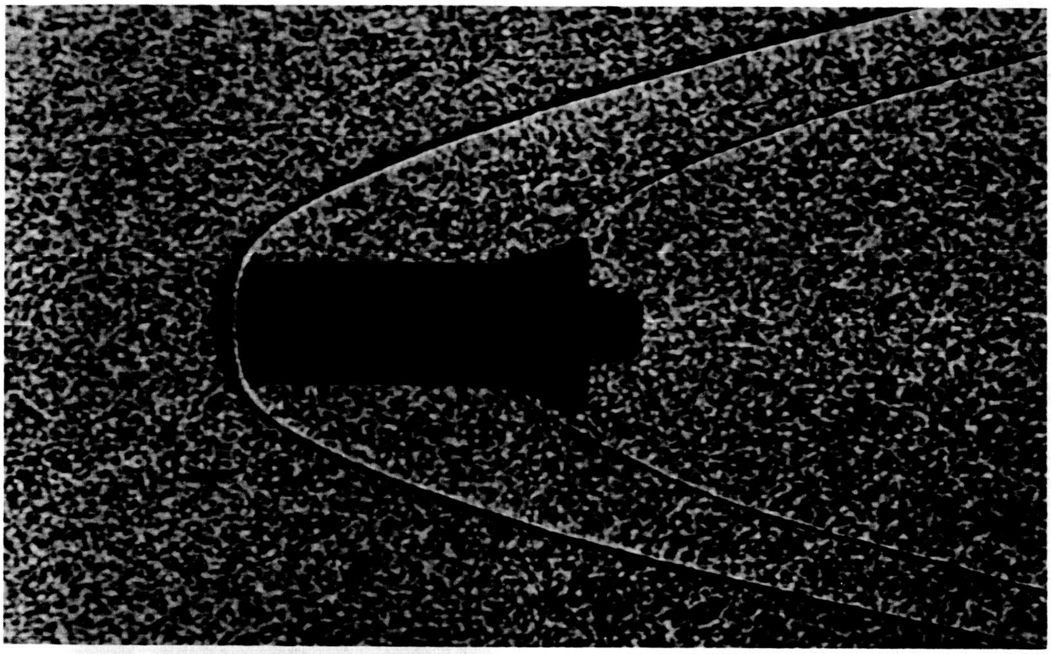
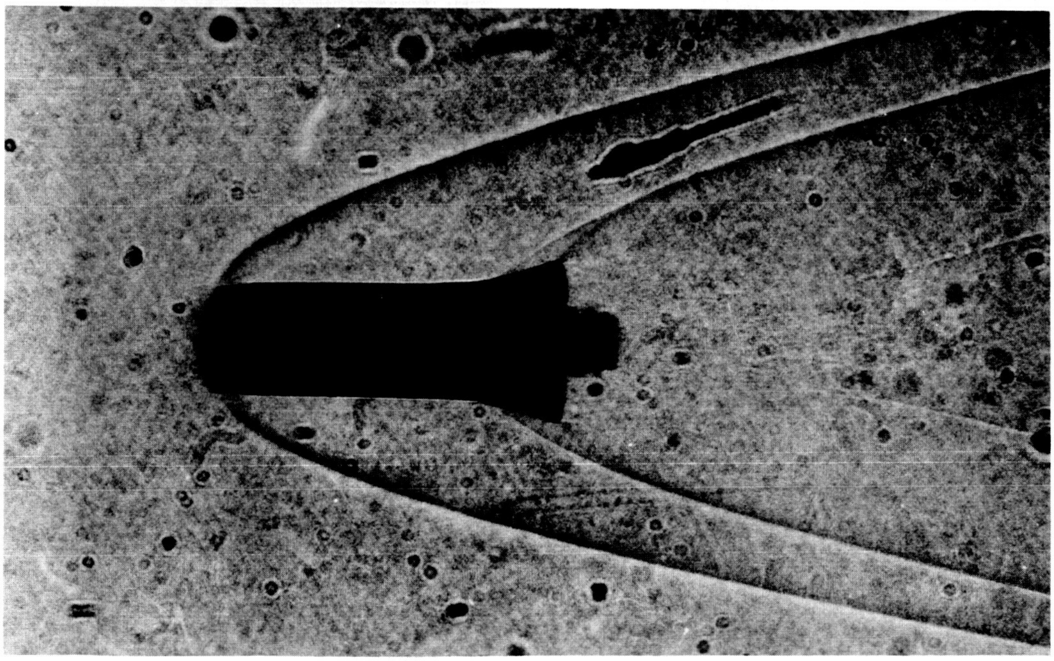


Figure 7.- Measured and calculated static stability in air and in a 90 percent carbon dioxide and air mixture; $\alpha_{R_{max}} = \pm 6^{\circ}$.



(a) M = 7.2 in air (countercurrent M = 2 airstream).



(b) M = 7.1 in quiescent carbon dioxide.

Figure 8.- Shadowgraphs showing the shock wave shape.

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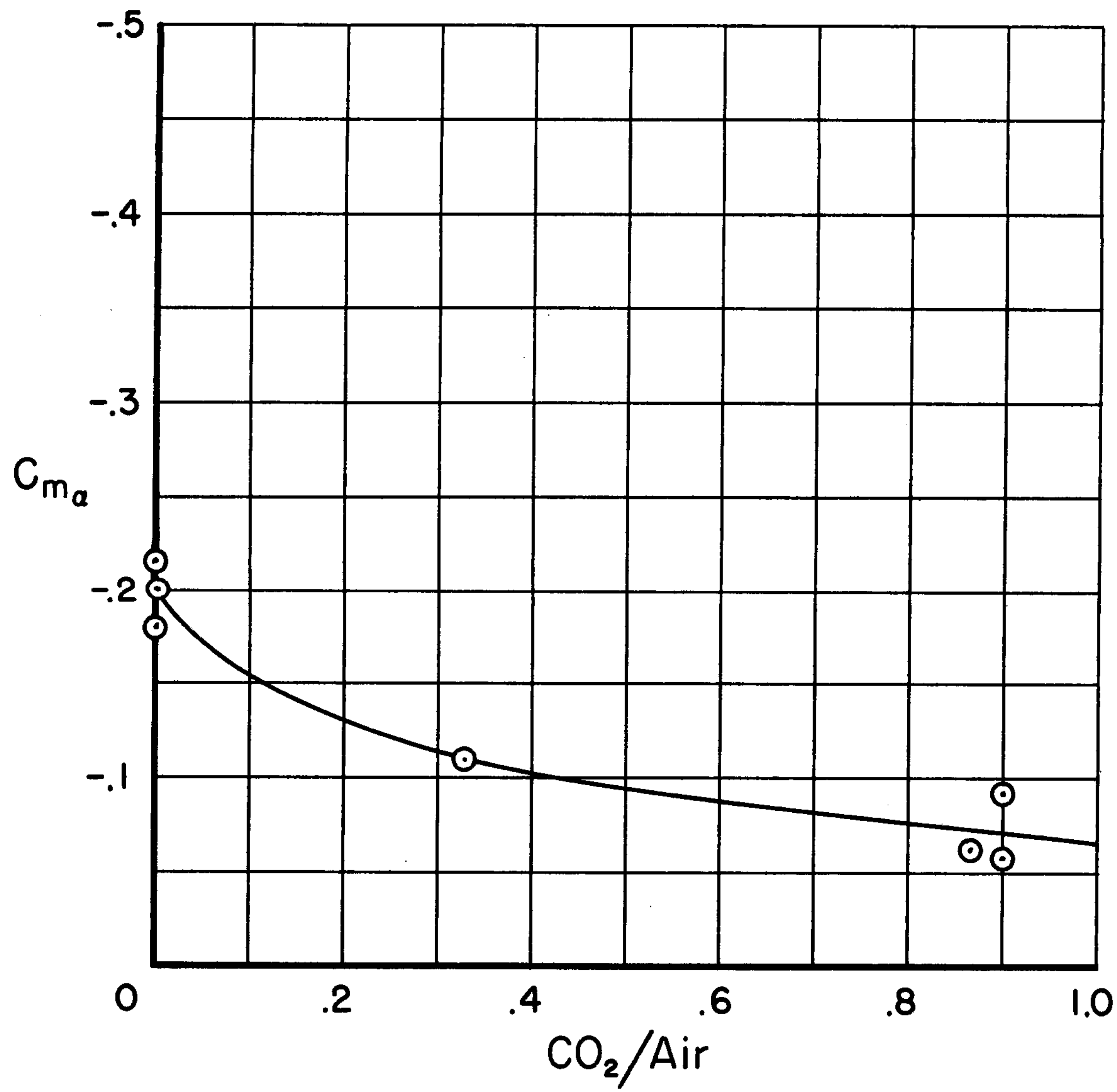

Figure 9.- Effect of gas mixture on the static stability derivative; $M = 7$, $\alpha_{R_{max}} = \pm 4^\circ$.